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We discuss the measurement of small optical surface absorption coefficients. A demonstration experiment was performed using a metalurgical strain gauge to measure 488 nm absorption on the surface of a glass plate. A strain of 10^{-6} resulted from absorption of 0.3 watts. The results are interpreted and the sensitivity of a proposed fiber optic strain gauge is discussed.

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CONTENTS

PHOTOTHERMAL MEASUREMENT OF OPTICAL SURFACE ABSORPTION USING STRAIN TRANSDUCERS

I. NEW REQUIREMENTS FOR OPTICAL SURFACE STUDIES

The high power density available both inside and outside laser cavities places stringent requirements on the performance of enhanced reflection coatings on mirrors, and for defect-free and low-bulk-absorption windows. At power densities on the order of 100 kW/cm^2 absorption of only 0.1%, i.e., 100 watts/cm^2, may be sufficient to cause coating degradation or window damage. The problem is exacerbated for long-pulse or c.w. operation since the damaged area will have increased absorption, leading to an avalanche of surface damage.

Reflection and Transmission radiometry are sufficiently precise to be able to characterize absorption of about 1% or more. At the level of absorption of concern to us here, less than 1%, radiometric methods fail to be accurate due to source drift, ambient light scattering, multilayer channeling, and other small effects which are often ignored. At least two other methods are available for measurement of these small surface absorptions: surface temperature measurement and photoacoustic methods.

The surface temperature method has proved useful in the study of surface and bulk absorption,[1] and as a calorimeter for bulk studies such as liquid water absorption in the visible[2]. The photoacoustic methods consist of two general arrangements. The first uses one side of the sample to close an opening in a small chamber containing an inert gas and a microphone[3]. Absorption of light by the sample causes a temperature rise, which is communicated to the microphone through a pressure change in the gas. The signal is detected by a phase-sensitive amplifier tuned to the chopping frequency of the light source. In the second photoacoustic arrangement the transducer, such as a piezoeletric crystal,[4,5] is bonded directly to the solid. The absorption induced strain is then monitored at the chopping frequency. In our proof-of-principle experiment a metallurgical strain gauge was used as the transducer.

The rest of this note discusses the use of strain transducers for measurement of small absorptions in solids. We first describe the details of a demonstration experiment, and then interpret the results in terms of current theory and modeling. We conclude with a discussion of how a new state-of-the-art sensitivity may be achievable by using one arm of a fiber optic interferometer as a strain transducer for detecting small absorptions. We believe that the system proposed here will be capable of measuring the extremely small surface absorptions of importance in the construction and diagnostics of high energy laser materials.

II. EXPERIMENT AND DISCUSSION

We obtained a general purpose metallurgical strain gauge[6] from the Material Science and Technology Division of NRL. Its active length was 1/2" and consisted of about twenty very closely spaced, fine copper alloy conductors. It was bonded to the center of the uncoated surface of a 2" × 2" × 1/8" glass plate. The other face of the plate was a front surface Al-coated mirror in poor optical condition. The strain gauge formed one arm of a bridge with a 6V battery power supply, as a shown in Fig. 1. The operation of the strain gauge is simple; a strain in the glass causes the resistance of the strain gauge to change, which unbalances the bridge. Phase sensitive detection is used when the source is modulated.

The 488 nm line from a Spectra-Physics tunable Ar^+ laser was directed (unfocused) at the mirror surface. The radiation was chopped at 10 Hz by a 50% duty cycle, variable speed chopper. No signal was observed at the lock-in amplifier, even when the transmitted beam struck the strain gauge. Due to both the relatively low power of the laser, and the fact that the surface was reflective, we decided to enhance the absorption. A china marker was used to put an opaque black spot, about 1/2" in diameter, at the center of the mirrored face and in line with the strain gauge mounted on the other side, as shown in Fig. 1. A 1.8 μV signal was observed at an average laser power of 0.3 watts at a 5 Hz chopping frequency. Figure 2 describes the response, at 5 Hz, as the power was gradually reduced. The linear relationship between observed strain and incident optical power is expected since we are certainly operating in the small strain (elastic) regime.
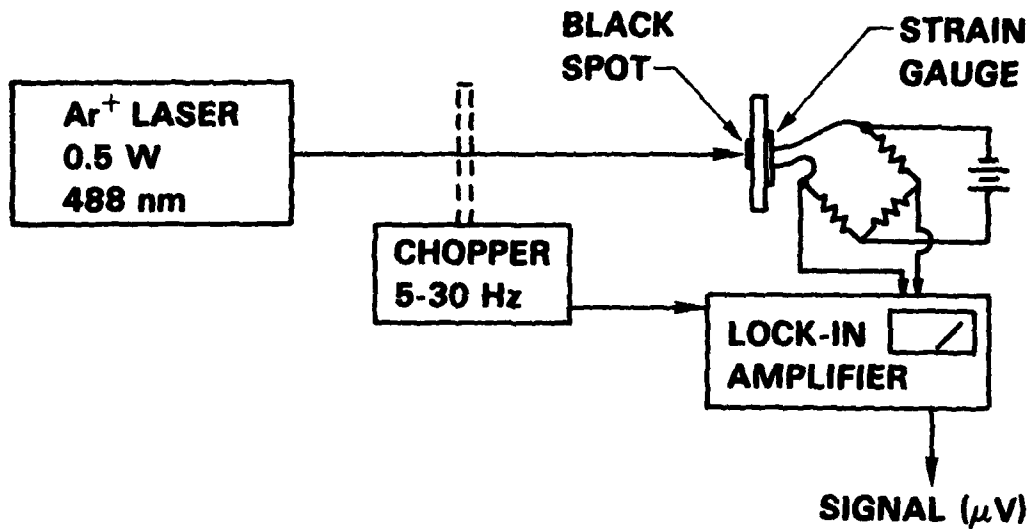
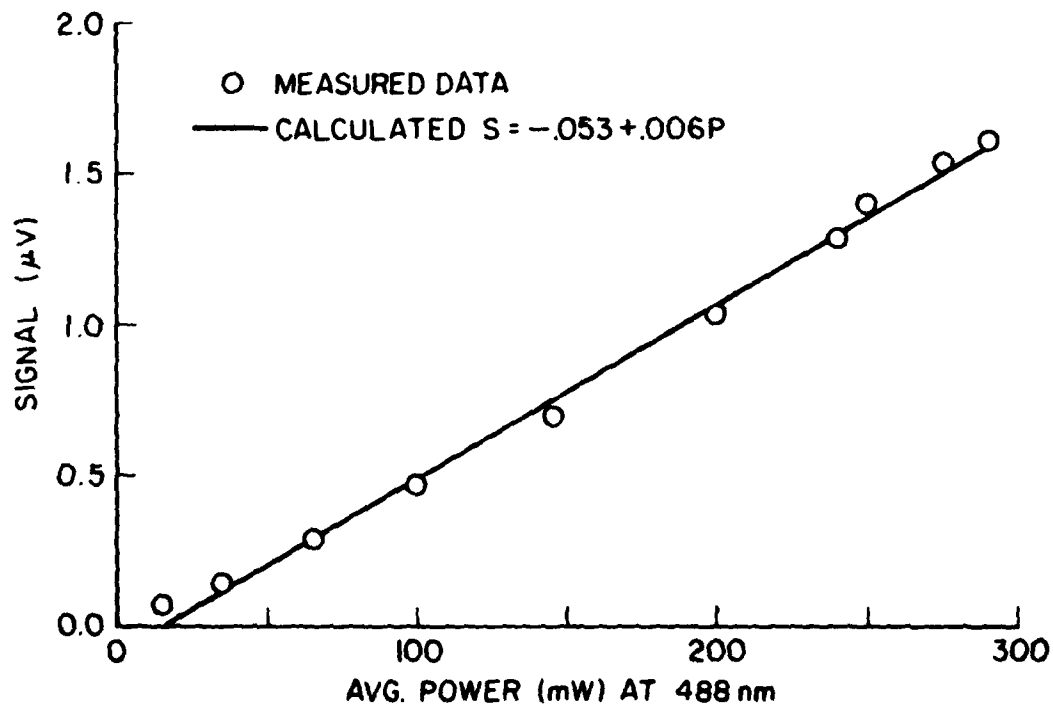Fig. 1 — Layout of the Experiment.

Fig. 2 — Response vs Laser Power.

We can calculate the mechanical strain as observed at the center of the glass plate by using the manufacturer's specification for the strain gauge performance: A gauge factor of 2.115 ± 0.5%, a bridge battery of 6V, and an observed $1 \mu V$ signal implies a measurement of 0.02μ strain, or $\Delta l = 2 \times 10^{-8} l_o$. This is observed on the back face of the glass, 1/8" thickness away from the site of the absorption.

We can also estimate the expected strain by using the known bulk properties of glass. For simplicity assume the glass is 2" diameter and 1/8" thick, i.e., a round disc rather than square. At a slow chopping frequency assume the total absorption of 0.03 Joules of light is completely converted into strain via thermal expansion of the bulk. The increase in size can be estimated[7]:

$$\pi (r + a)^2 l - \pi r^2 l = \beta V (\delta T)$$

for $a \ll r$,

$$2\pi r a l = \beta V (\delta T). \tag{1}$$

For optically thick (total) absorption,

$$Q = C_p \rho \ V (\delta T) = E \tag{2}$$

hence we have

$$\frac{a}{E} = \frac{\beta}{2\pi r C_p \rho l} \text{ (optically thick)} \tag{3}$$

and, using the parameters listed in table I, we calculate

$$a \approx 1 \times 10^{-8} \text{ cm}$$

which gives a strain

$$\frac{a}{r} \approx 4 \times 10^{-9}$$

and an approximate temperature rise

$$\delta T \approx 8 \times 10^{-3} \text{ }^\circ K.$$

We have made several simplifying assumptions in order to estimate the strain. We have ignored thermal lag, assumed uniform temperature distribution, and made no allowance for thermal loss by convection, ect; yet this crude estimate predicts a strain 20% of the measured. And, we could expect the prediction to come out low because the thermal energy is probably more localized at the center of

Table I Assumed Properties of the Glass (8)

δT = temperature increase

a = increase in radius

r = original radius = 2.54 cm

l = thickness = 0.1375 cm

V = volume = 2.79 cm^3

β = volume expansion coefficient = 10^{-6} $°K^{-1}$

Q = absorbed thermal energy $\approx$ 0.03 Joules

E = optical energy in one-half cycle $\geqslant Q$

C_p = specific heat = 0.7 Joules/gr. °K

ρ = mass density = 2.0 gr/cm^3

κ = thermal conductivity = 1.5 × 10^{-2} W/cm °K

α = thermal diffusivity = $\dfrac{\kappa}{\rho C_p}$ = 1.1 × 10^{-2} $\dfrac{cm^2}{sec}$

B = bulk modulus = $\left[\dfrac{1}{V} \left. \dfrac{\partial V}{\partial P} \right|_T \right]^{-1}$ = 3.3 × 10^5 Bar

the blank. This demonstrates that our measurement and estimate agree within an order of magnitude. A strain of 10^{-8}, incidentally, over a 1 cm length, is $10^{-4}\mu$m displacement, or about 10^{-4} of a fringe at 1 μm wavelength.

The measured frequency response of the device is described in Fig. 3. The chopper speed was increased in very small steps, and the lock-in phase control was adjusted for maximum amplitude at each point. One expects a decreasing response at increased chopping frequencies. The thermal modulation (A.C.) seen at the strain gauge will "wash out" into a D.C. temperature increase at higher frequencies. This is borne out by our data. We curve fit the data in Fig. 3 to an expression of the form
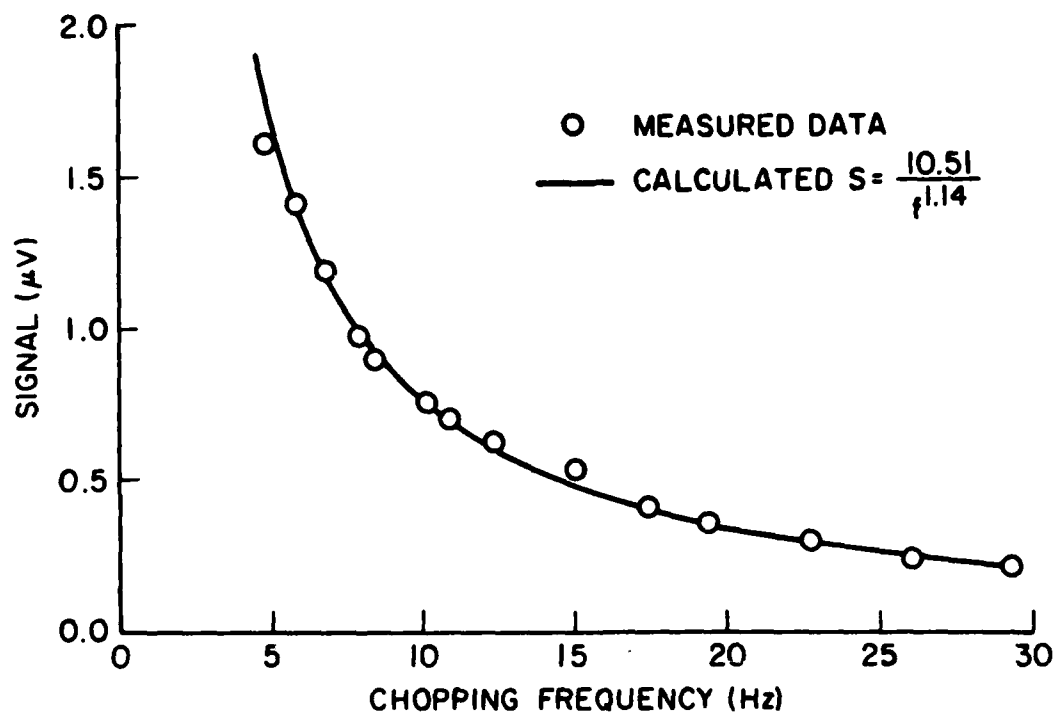
$$S = k\, f^{-n}$$

Fig. 3 — Response vs Frequency.

and obtained the best fit for $n = 1.14$, where S is the observed signal, k is a constant, and f is the the chopping frequency. The Rosencwaig-Gersho (R-G) theory[9] predicts $n = 1.0$ for surface absorption, and $n = 1.5$ for bulk absorption, but for the arrangement where a microphone is coupled to the solid by an inert gas. The surface absorption frequency behavior applies to our case since we induced complete surface absorption using the opaque spot.

Although until now we have assumed an opaque surface, we can apply the same technique to an optically thin (small absorption) material. For this case Eq. 2 becomes

$$Q = E (1 - e^{-\alpha l}) \approx E \alpha l$$

and Eq. 3 then becomes:

$$\frac{a}{E} = \frac{\beta \cdot \alpha}{2\pi \, r \, C_p \rho} \quad \text{(optically thin)}. \tag{4}$$

Hence we see with Eq. 4 how the measurement principle demonstrated with the strain gauge and an opaque surface may be applied to the measurement of small absorption coefficients for coatings on windows; a fraction of the incident energy causes a measurable strain a, which is proportional to the absorption coefficient α. The beam energy and bulk properties are either known or are measurable.

One question is what to call the measurement technique just described: photoacoustic or photothermal? We tend to think of phenomena at $5 - 30$ Hz as thermal, and higher frequency phemonena (20 Hz $-$ 20 kHz) as acoustic. Tam and Patel[7] discuss a similar question in their article on the visible absorption of liquid water. They point out that absorbed optical energy can appear as both thermal and acoustic energy. The thermal component in proportional to the temperature change (δT), but the acoustic energy is porportional to a mean square displacement, and the displacement is porportional to δT, giving an acoustic temperature dependence of $(\delta T)^2$.

The relative magnitude of the two energies can be estimated during one half cycle of illumination using the parameters in Table I:

(1) $E_{thermal} = \rho \, C_p \, V \, (\delta \, T)$

$$= \left[\frac{2 gr}{cm^3}\right] \left[\frac{0.7 \, J}{gr \, {}^\circ K}\right] (2.8 \, cm^3) \, (8 \times 10^{-3} \, {}^\circ K)$$

$$= 3.1 \times 10^{-2} \, ergs$$

(2) $E_{acoustic} \approx (\pi \, a^2 \, l) \, B$

$$= (\pi) \, (1 \times 10^{-8} cm)^2 \, (.1375 cm) \left[3.3 \times 11^{11} \, \frac{dyne}{cm^2}\right]$$

$$= 1.4 \times 10^{-5} \, ergs.$$

$$\therefore \frac{E_{thermal}}{E_{acoustic}} \approx 2000.$$

By Eq. (1)

$$u = \frac{\beta \, V}{2 \pi \, r \, l} \, (\delta \, T).$$

so we can define an acoustic coupling coefficient $\gamma_{ac} = \left[\frac{\beta \, V \, B}{2 \, r}\right]$, and by (2) a thermal coupling

coefficient $\gamma_{th} = C_p \, p \cdot V$ (optically thick) or $\gamma_{th} = (C_p \, p \, V) \alpha \, l$ (optically thin). Then we have the simple expression,

$$Q = E_{thermal} + E_{acoustic}$$

$$= \gamma_{th} \, (\delta \, T) + \gamma_{ac} \, (\delta \, T)^2.$$

There are several practical reasons why the acoustic regime has been prefered. Microphones and piezoelectric detectors have optimum response at frequencies above our "thermal" regime. Ambient noise is also lower at higher frequencies, and most practical communications equipment operate at higher frequencies than employed here. But the photothermal regime has some distinct advantages, given the proper detector, as we show in the next section.

III. A PROPOSED FIBER OPTIC STRAIN GAUGE

Optical techniques have been used in deformable mechanics for many years. One example is the use of "optical levers" for measurement of small torsional displacements. Another example is the use

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of transparent substitute components and crossed polarizers for observation of critical stress points. What we propose is the use of an optical detector for measurement of the photothermally induced stress caused by the absorption of light. Rather then using the strain gauge described previously, we propose bonding several turns of one arm of a fiber optic interferometer to the substrate. To balance the interferometer the other arm could be similarly bonded to an unexposed substrate, although use of some FOSS (Fiber Optic Sensor System Program) electronics may make this unnecessary.

Recent advances by NRL researchers have enabled the measurement of fringe shifts as small as 10^{-7} fringe at 0.63 μm wavelength in a fiber optic interferometer[10]. Our demonstration experiment involved measurement of a strain of 2×10^{-8}, or about 2×10^{-4} fringe at 1 μm over a 1 cm path. This reasoning ignores possible index of refraction change with temperature. A more accurate expression is[4]

$$\frac{d\phi}{dT} = \frac{2\pi L}{\lambda} \left[\frac{n}{L} \frac{dL}{dT} + \frac{dn}{dT} \right]$$

(5)

where L = length, ϕ = phase, T = temperature, n = index of refraction.

The photothermal spectroscopy practiced by Campillo, et.al.,[11] involves intersecting a probe beam with an interferometer beam in a transparent material and is vaguely similar to what we propose. Their arrangement measures modulation in the index of refraction where our arrangement measures modulation in the fiber strain. Our device is substantially simpler and more appropriate for bulk studies. Three orders of magnitude sensitivity is gained by being able to measure 10^{-7} fringe shift, and an additional two orders or so is available by bonding one meter rather than one cm to the substrate. Drift can be eliminated electronically as has been recently demonstrated[12]. This translates to an ability to measure a strain as low as 10^{-13}, or 10^{-5} Å over a 1 cm length, where a 10^{-4} Å capability in a fiber-optic interferometer[10] has been demonstrated.

Substitition of 10^{-13} for a radial strain $\left(\frac{a}{r} \right)$ into Eq. (1) yields a temperature change of 3×10^{-8} °K, and a net absortption of 1 μwatt at 5 Hz modulation. Although these numbers are very

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small, they are not unphysical. The fundamental limit for observing temperature change is set by the level of thermal fluctuations in the substrate. This is given by[13]

$$\overline{(\Delta T)^2} = \frac{k_B T^2}{C_v} \qquad (6)$$

and gives $(\Delta T)_{rms} \approx 2 \times 10^{-10}\ °K$ for our glass substrate. Since our projected sensitivity is still two orders of magnitude above the fundamental limit set by (6), we feel that ambient sources of noise may prove to be the realistic limitation. We are pursuing the fiber optic strain gauge concept and plan to build a prototype in the very near future.

We acknowledge helpful technical discussion with Allen Tveten, and the assistance of Robert Bayles of the Material Science and Technology Division for lending us the strain gauge.

IV. References

1. M. Hass, J.W. Davisson, H.B. Rosenstock, and J. Babiskin, "Measurement of Very Low Absorption Coefficients by Laser Calorimetry", *Applied Optics* **14**, 1128-30 (1975).

2. M. Hass and J. Davisson, "Absorption Coefficient of Pure Water at 488 and 514.5 nm by Adiabatic Laser Calorimetry", *J. Opt. Soc. Am.* **67**, 622-4 (1977).

3. A. Rosencwaig, "Solid State Photoacoustic Spectroscopy," in *Optoacoustic Spectroscopy and Detection*, Y-H Pao ed., Academic Press, NY (1977).

4. A. Hordvik, "Measurement Techniques for Small Absorption Coefficients: Recent Advances," *Applied Optics* **16**, 2827-33 (1977).

5. A. Hordvik and H. Schlossberg, "Photoacoustic Technique for Determining Optical Absorption Coefficients in Solids," *Applied Optics* **16**, 101-107 (1977).

6. Mico-Measurements Inc., Model EA-06-125AC-120, Resistance = 120 Ω ± .3%, Gauge Factor = 2.115 ± 0.5%, transverse sensitivity = ± 0.4%.

7. A.C. Tam and C.K.N. Patel, "Optical Absorptions of Light and Heavy Water by Laser Optoacoustic Spectroscopy," *Applied Optics* 18, 3348-58 (1979).

8. American Institute of Physics *Handbook*. 3rd Edition, Ch. 2, 1972.

9. A. Rosencwaig and A. Gersho, "Theory of the Photoacoustic Effect with Solids." *J. Appl. Phys.* 47, 64-69 (1976).

10. D.A. Jackson, A. Dandridge, and S.K. Sheem, "Measurement of Small Phase Shifts Using A Single-Mode Optical-Fiber Interferometer", *Optics Letters* 5, 139-141 (1980).

11. A.J. Campillo, H-B Lin, C.J. Dodge, and C.C. Davis, "Stark-Effect Modulated Phase-Fluctuation Optical Heterodyne Interferometer for Trace-Gas Analysis," *Optics Letters* 5, 424-6 (1980).

12. D.A. Jackson, R. Priest, A. Dandridge, and A.B. Tveten, "Elimination of Drift in a Single-Mode Optical Fiber Interferometer Using a Piezoelectrically Stretched Coiled Fiber", *Applied Optics* 19, 2926-29 (1980).

13. L.D. Landau and E.M. Lifshitz, *Statistical Physics*, Trans. J.B. Sykes and M.J. Kearsley, Addison Wesley, 2nd Ed., 1969, p. 350, 3rd ed., 1980.